NISTIR 6038

2-D True Time Delay Generation Using Fiber Chirp Gratings and Acousto-Optic Beam Deflectors

Eung Gi Paek
Information Technology Laboratory
National Institute of Standards and Technology*
Gaithersburg, MD 20899

Joon Y. Choe
Tae K. Oh
Naval Surface Warfare Center
Dahlgren, VA 22192

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4ns to 100 ns and $\Delta\tau_{min}$ = 0.04 ps to 1 ps. Therefore a broad range of time delays (from 0.04 ps to 100 ns) is required. Furthermore, the time delays must be reconfigured within 10 μs. Therefore, the TTD problem is certainly one of most challenging interconnection problems.

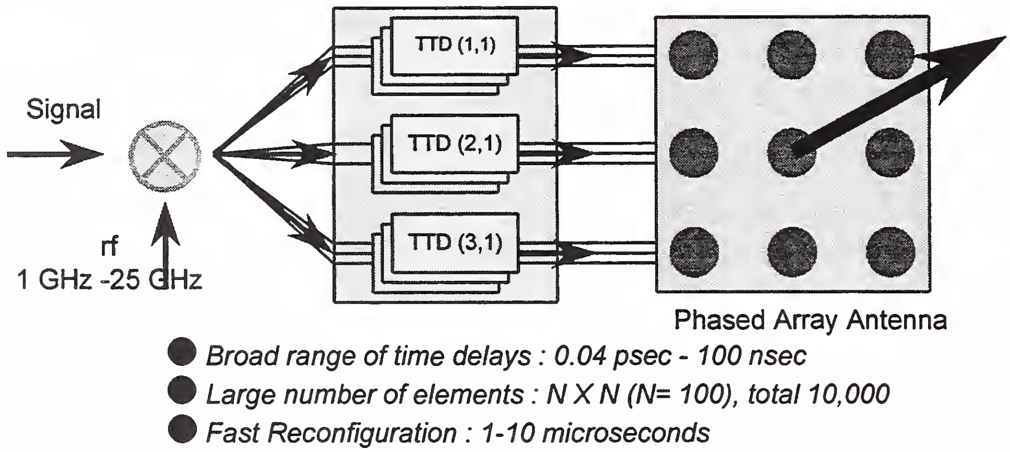


Fig. 1. True time delay generation problem.

Photonics provides a powerful means of interconnection particularly for the massive 2-D cases and at high speed: the large number of interconnections can be achieved through free-sapce without causing electromagnetic interference even at high speed. Besides, photonics has many unique parameters such as wavelengths, natural parallelism along both dimensions, and free-space interconnection that does not require physical point-to-point contacts. A number of photonic TTD approaches have been demonstrated using fiber delay lines [2, 3], highly dispersive fiber prisms [4], fiber Bragg gratings [5-7], liquid crystal spatial light modulators [8], and waveguides [9, 10]. Multiplexing schemes include time-division multiplexing using optical switches, space-division multiplexing, and wavelength-division multiplexing. However, most of the proposed systems to date require a tremendous amount (typically 10^7) of devices. Especially for 2-D implementation, the device complexity dramatically increases by approximately two orders of magnitude compared with the one-dimensional cases, making its implementation prohibitively costly.

In this paper, we propose a new ASTRO 2-D true time delay generation architecture [11] that can significantly reduce device complexities by combining free space optics and guided optics. We will first describe the concept for one-dimensional (1-D) beam steering cases and its 2-D extension will be explained later.

2. ASTRO (ACOUSTICALLY STEERED AND ROTATED) TTD - 1-D Cases

Figure 2 (left) illustrates the desired time delays of antenna elements to generate 1-D beam steering along the horizontal direction. The antenna elements in the same column have the same amount of time delay and the time

delay increases linearly along the row (horizontal) direction. Our approach to generate time delays can be considered as two steps: first, to generate a time-delayed grating-like light pattern and second, to image the light pattern on the array of photo-detectors. To couple the light from free space to a photo-diode that is normally small at high speed, an array of diffractive optical elements or lenslets can be used.

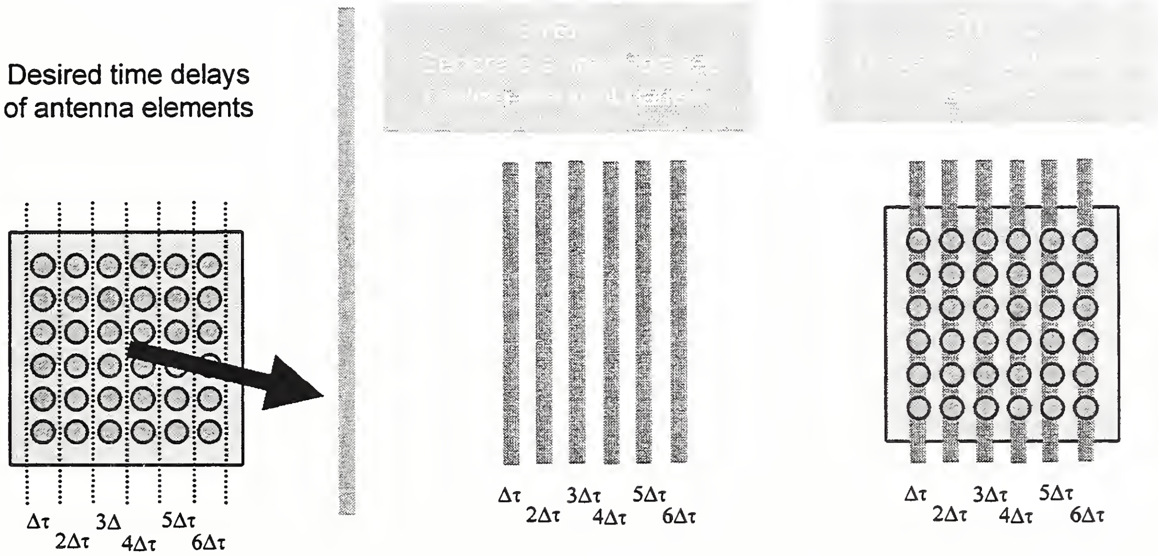


Figure 2. 1-D beam steering.

Figures 3 shows a schematic diagram of our approach to generate 1-D time delays. Light from a broadband light source is modulated by an optical modulator and is coupled to a single fiber through an optical circulator. The single fiber contains an array of fiber chirp gratings with different linear chirp ratios to encode various linear chirp time delays by wavelengths. The light reflected from each of the fiber chirp gratings is amplified by an optical amplifier and is dispersed by an acousto-optic spectrometer (AOS) to form a spectrum at the output plane. By adjusting the acoustic frequency applied to the acousto-optic beam deflector (AOBD), the portion of the spectrum with desired linear chirp time delay can be selected through a fixed output window, without requiring fast tunable lasers, switches or beam combiners/splitters.

3. ASTRO TTD – 2-D extension

For the 2-D extension, most existing approaches use cascading methods [4,6,7] that involve tremendous amounts of device complexity (from N to N^2 where N is the number of antenna elements along one dimension, typically 100) and loss of optical transparency. Our method is significantly different from the existing methods and utilizes our novel ultrafast non-mechanical image rotation. The concept of the 2-D extension can be understood

from the analogy of a diffraction grating. As is shown in Figure 4, as a diffraction grating is rotated about the z-axis, the pointing vector of the diffracted light covers the entire side of the cone whose azimuth angle θ with respect to the z axis is determined by the grating period. Such a 2-D extension by rotation greatly simplifies the device complexity from N^2 to N.

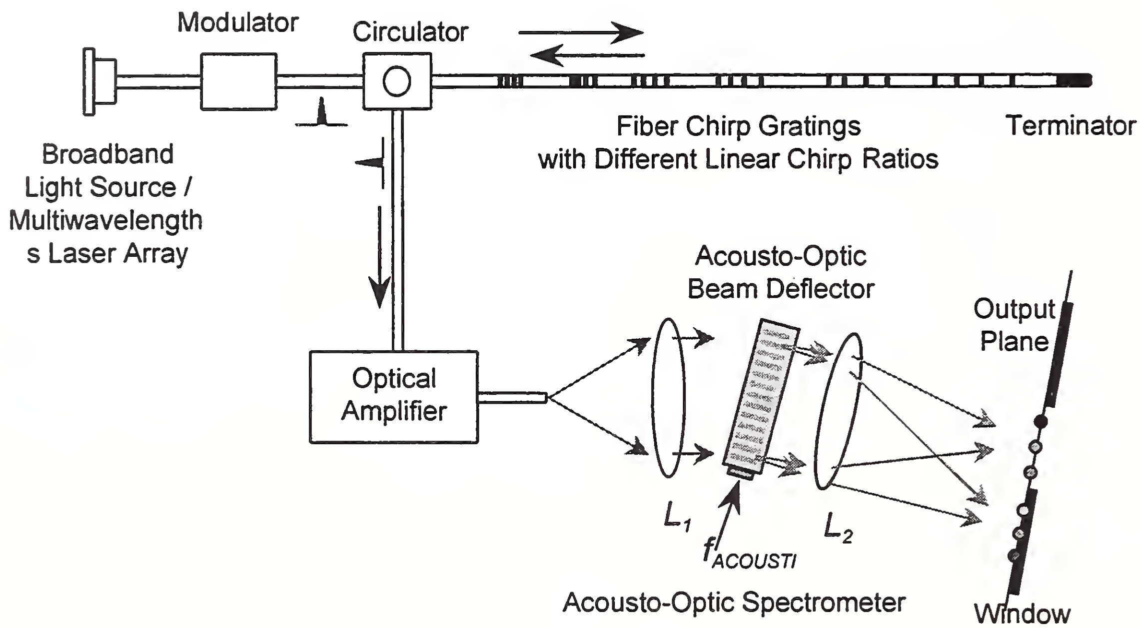


Fig. 3. 1-D true time delay generation.

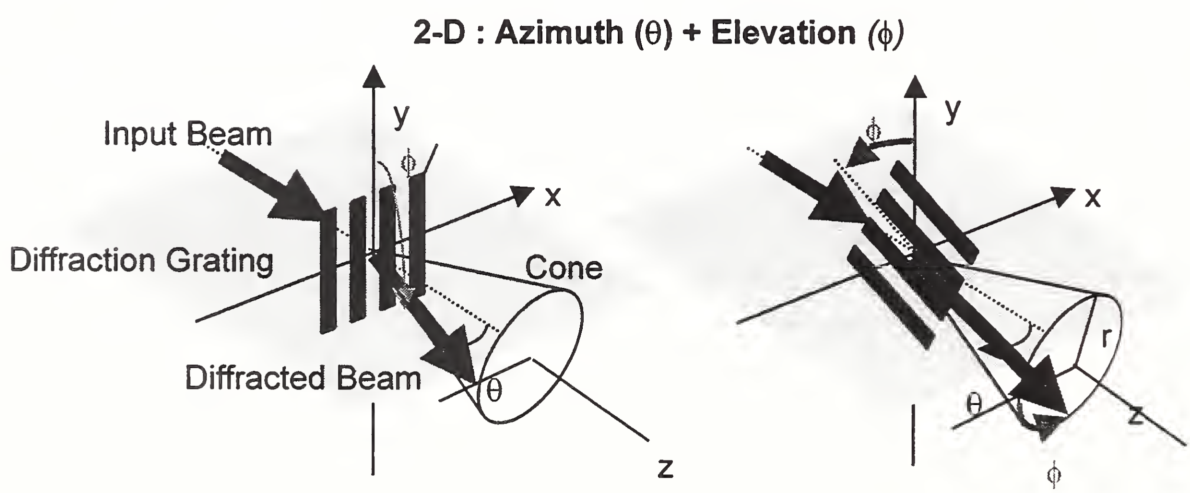


Fig. 4. 2-D extension.

However, the 2-D extension by rotation requires a means of fast image rotation that needs to be achieved within 10 μs. To meet the requirements, we devised a new ultrafast non-mechanical image rotation method using acousto-optic beam deflectors as is shown in Figure 5. The concept is based on the principle of the conventional dove prism which consists of three parts : the first part is a wedge prism to direct the incoming beam onto the bottom (or top) mirror surface of the second part. The bottom mirror reflects the light and the third part (second wedge) aligns the beam along the original direction. In our non-mechanical image rotation, each of the wedges is replaced by an xy-AOBD (acousto-optic beam deflector) and the reflecting mirror is also replaced by a multi-facet cylindrical mirror (bottom). In this way, a 2-D image pattern can be rotated to an arbitrary angle in a programmable manner within a few microseconds.

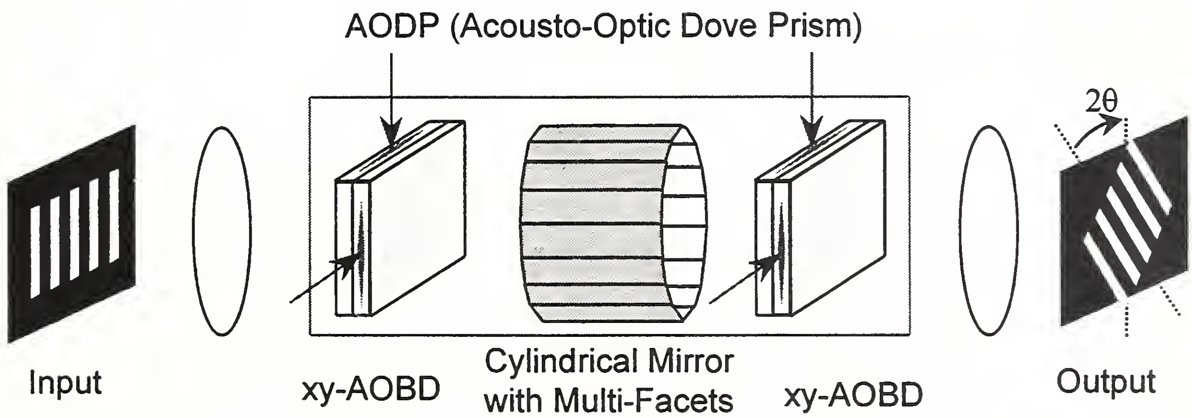


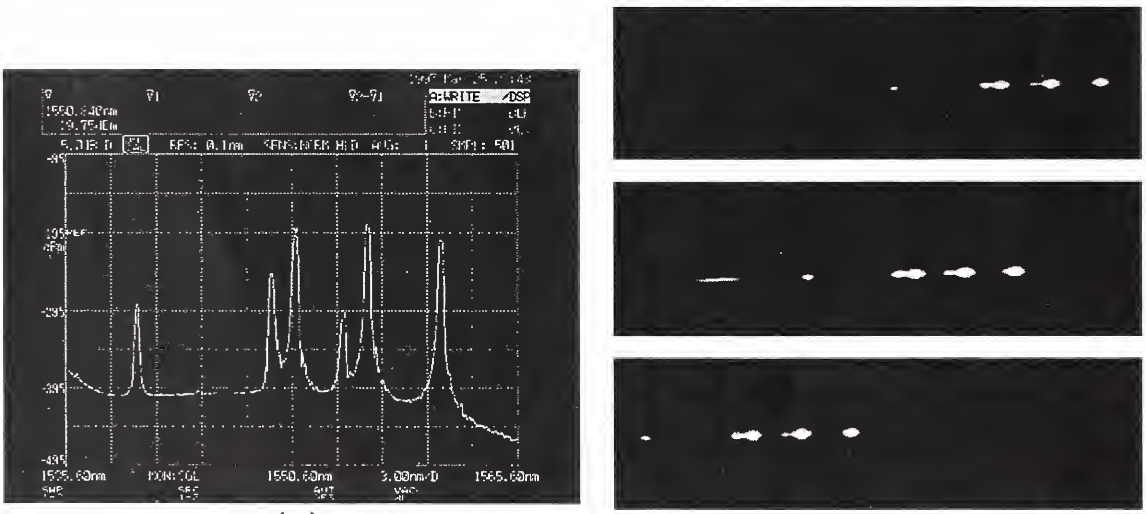
Fig. 5. 2-D extension using an acousto-optic dove prism (AODP).

4. EXPERIMENTAL RESULTS

To demonstrate the concept of our system architecture, two experimental setups are constructed using optical components available in our laboratory. The first one is for 1-D and is intended to test encoding and decoding of wavelength division multiplexing using fiber Bragg gratings and an AOS as shown in Figure 3. Light from a 10 mW ASE (amplified spontaneous emission) light source is modulated by an acousto-optic modulator (Brimrose, Model No. IPF-1000-1550-3FP, Fiber pigtailed InP [13]) to generate an optical pulse with a pulsewidth of approximately 20 nsec. The optical pulse is coupled to a single-mode fiber through an optical circulator (Optics for Research, Model No. OCT-3-IR2 with FC/APC connectors). Six fiber Bragg gratings are connected in series with patchcords in between so that the first three FBG's (from left to right in the Figure 3) are separated by six meters (corresponding to 60 ns time delay) and the other three FBG's are separated by six meters (120 ns). The Bragg wavelengths are chosen around 1550 nm to permit the use of Erbium doped fiber amplifiers (EDFA's), and spectral resolution is around 0.1 nm. The light reflected from the fiber gratings is split into two : one beam goes to a conventional optical spectrum analyzer and the other to our home-made acousto-optic spectrometer which consists

of a collimating lens, L_1 (f=10 cm), an acousto-optic beam deflector (AOBD) and a Fourier transform lens, L_2 (f=38 cm). The AOBD is made of slow shear mode TeO_2 material and has a time bandwidth product of approximately 1,000. The output spectrum is detected by an infrared vidicon camera (Hamamatsu, Model No. C2741).

Figure 6 compares the spectra obtained from the two spectrum analyzers : (a) a commercial optical spectrum analyzer and (b) our home-made acousto-optic spectrum analyzer. Both clearly resolve the six wavelengths. In addition, the acousto-optic spectrometer is capable of shifting the whole spectrum rapidly (within 10 microseconds) along the horizontal direction by varying the acoustic frequencies; 40 MHz (Top), 45 MHz (middle), and 55 MHz (bottom).



(a) (b)

Fig. 6. Spectra obtained from (a) a commercial optical spectrum analyzer and (b) our home-made acousto-optic spectrum analyzer for acoustic frequencies : 40 MHz (Top), 45 MHz (middle), and 55 MHz (bottom).

Figure 7 shows six time-delayed pulses obtained after reflection from each of the six FBG's. The optical pulses are detected by a photodetector (Newport Corp. Model AD-300). The pulse on the top left corner represents an electrical pulse applied to the acousto-optic modulator. The desired time delays (60 ns for the first three and 120 nsec for the other three pulses shown on the bottom) are generated as scheduled. Temporal resolution in this experiment was limited by the slow modulation speed of the acousto-optic modulator and the detector. A finer time-delay generation can be obtained by using a faster electro-optic modulator and a detector with an array of closely spaced FBG's.

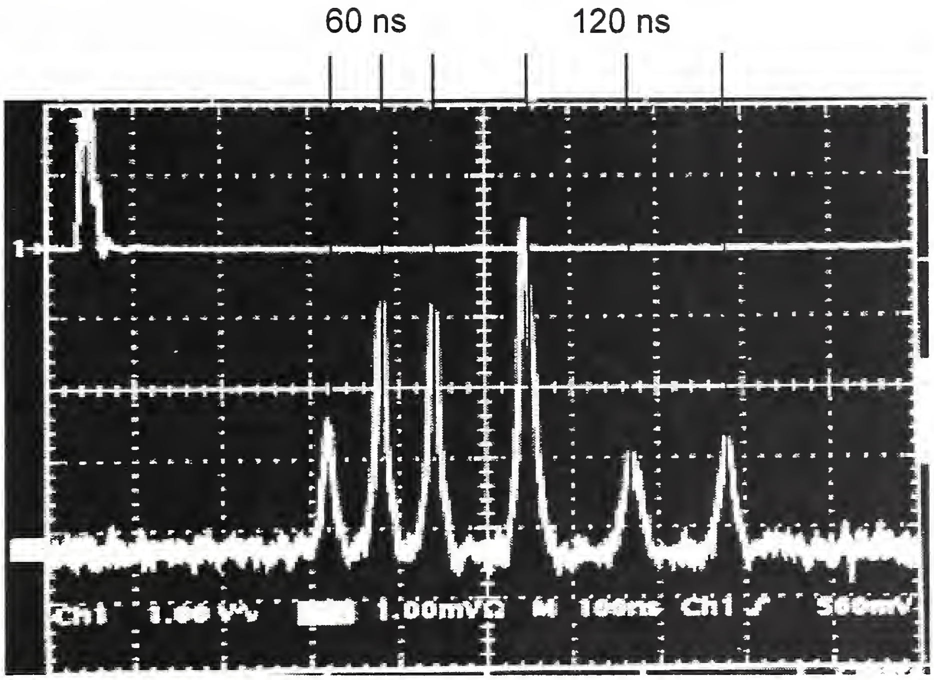


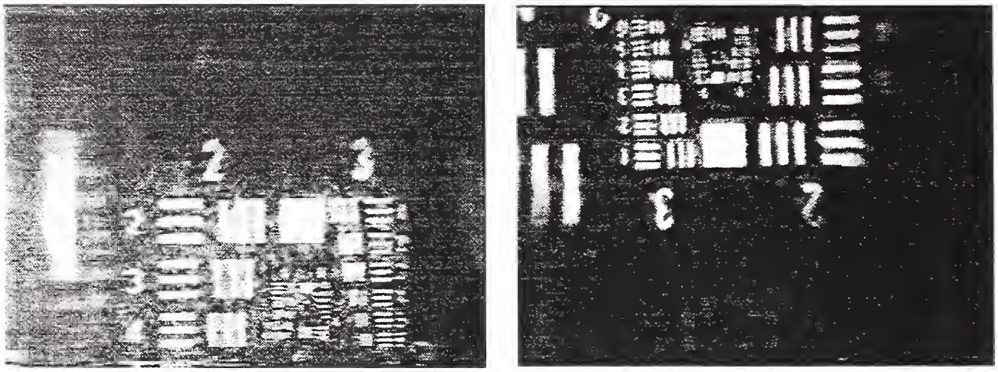
Fig. 7. Time delayed pulses after reflection from the six FBG's.

To prove the concept of the non-mechanical image rotation, we constructed an experimental setup shown in Figure 5. A 5 mW HeNe laser is used as the light source. After beam expansion and spatial filtering, the magnified collimated beam illuminates an input image recorded on a transparency. The light passing through the input transparency is deflected by a pair of crossed AOBDs (slow shear mode TeO_2 crystals with a large input angular bandwidth) and is focused by a lens (focal length = 36 cm) on the surface of the cylindrical polygon mirror. In this initial demonstration intended for proof of concept, only two mirror facets oriented at a right angle are used. After the multi-facet mirror, the beam is reflected back to pass through the same lens and xy-AOBDs and is detected by a CCD after a beam splitter.

Figure 8 illustrates an experimental result obtained from our optical system. Since the two mirrors are at a right angle, the two images are rotated by 180 degrees (twice the angle between the two mirrors). A real-time image rotation has been achieved within 10 µsec with a 6 mm aperture in front of the AOBDs. Also, rotations to other angles have been separately confirmed. A multi-facet cylindrical mirror is being designed to permit rotation to many different angles.

Besides the reduced complexity, our proposed system has a lot of advantages over conventional systems: First, the system is simple, requiring only a single fiber for time delay generation, without requiring fast tunable lasers, optical switches, splitters or combiners. Second, there are no intermediate photon-to-electron conversion processes. This feature is important for bi-directional communications. Third, multiple beam steering is possible by adding

many acoustic frequencies to the AOBD. Fourth, an optical amplifier can be used even "after" time delay generation, since time-delayed signals are still within a single fiber. Finally, the single fiber is portable, to permit easy remoting.



(a) (b)

Fig. 8. Ultrafast non-mechanical image rotation

5. CONCLUSION

In conclusion, we have described a new ASTRO 2-D TTD generation architecture by using fiber Bragg gratings, an acousto-optic spectrometer and a novel acousto-optic dove prism. Through the two experimental setups described above, the basic concept of the idea has been separately demonstrated. The next step is to combine the two setups to implement a complete 2-D TTD generation.

There are two important issues to be raised about the proposed architecture. First, the number of available wavelength channels is limited by the time-bandwidth product of an AOBD, which is typically less than 1,000 at 1.55 μm. This limitation can be relaxed by choosing other visible wavelengths. However, in this case, Erbium-doped fiber amplifiers cannot be used. We are currently developing a new method to significantly increase the resolution of the acousto-optic spectrometer within the EDFA passband. A second big issue is the light budget. Most of insertion loss in this architecture is due to the AOBDs. Each AOBD has 3 dB to 6 dB insertion loss, and the system requires 5 AOBDs, causing 15 dB to 30 dB insertion loss. Besides, the window sampling will cause another 10 dB to 20 dB light loss. Such a loss can be significantly reduced by using a fast tunable laser. Also, the light from the AODP could be accurately coupled to a detector array by using a lenslet array, to further reduce the loss. In order to increase spectral brightness and to reduce the spontaneous noise effect of the ASE source, an array of multi-wavelength laser diodes can be used.

6. ACKNOWLEDGMENT

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13. Certain commercial equipment or components are identified in this paper only to specify the experimental procedure adequately. They are not necessarily the best available for the purpose but were simply available in our laboratory for these proof-of-concept experiments.